BIOFIDELITY EVALUATION OF DYNAMIC AND STATIC RESPONSE CHARACTERISTICS OF THE THOR LX DUMMY LOWER EXTREMITY

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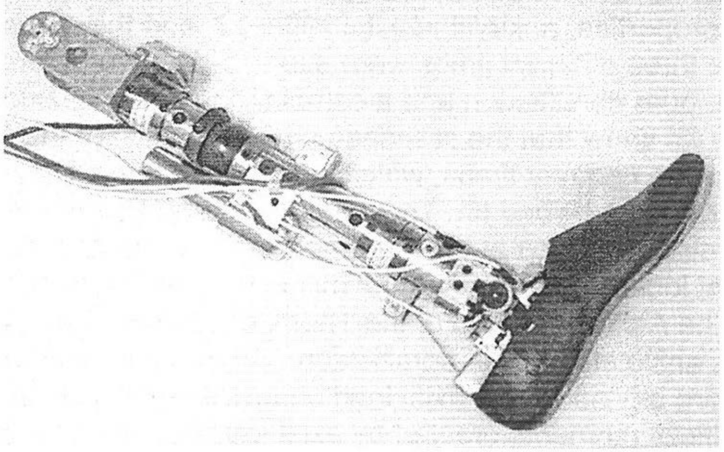
ABSTRACT

This study evaluates the biofidelity and response characteristics of the Thor Lx dummy lower extremity prototype. Static and dynamic tests were performed to evaluate its response relative to that of cadavers and the Hybrid III (45° dorsiflexion ankle and soft joint stop). Static tests determined the ankle joint moment properties, ankle/tibia axial stiffness, and the mass and moments of inertia. The three different limbs were subjected to two different types of dynamic tests: pure dorsiflexion and a combination of dorsiflexion and axial load. The results show that the response characteristics of the Thor Lx better reflect those of the cadaver limbs, which indicates that the Thor Lx design is an improvement over the Hybrid III. The continuous ankle joint stiffness eliminates joint property discontinuities at the extreme ranges of motion, and the non-concentric joint locations of the Thor Lx mimic the ankle and sub-talar joints in the human. The Achilles tendon of the Thor Lx serves as passive musculature and increases ankle stiffness in dorsiflexion. A compliant element in the tibia shaft gives more biofidelic tibia axial load characteristics, and the straight shaft eliminates artificial moments created by axial loading. With its design modifications and comprehensive instrumentation package, the Thor Lx is capable of providing a more complete and biofidelic assessment of lower limb response and injury risk.

INCREASED ATTENTION GIVEN TO lower extremity injuries in car crashes has prompted more in-depth lower extremity research. According to Burgess *et al.*, lower extremity injuries accounted for 40% of trauma center victims' treatment costs (1995). Pattimore concluded that 68% of the skeletal injuries sustained by restrained occupants in frontal collisions occur below the knee (1991). While injuries to the lower extremities are rarely life threatening, the costs of treatment and impairment are often high (Dischinger, 1994).

The Thor Lx is the second design iteration of the Advanced Lower Extremity (ALEX) originally developed by the National Highway Traffic Safety Administration (NHTSA) in 1994. The Thor Lx was developed to be an integral component of NHTSA's Thor advanced frontal ATD, but was also designed with the capability to retrofit directly to the 50th percentile male Hybrid III ATD. Its goal is to represent more realistically the human lower limb and replace the Hybrid III leg for crash testing. Features of the Hybrid III leg did not accurately represent the human anatomy, and these features significantly affected the data obtained in testing as well as the ability to consider the response to be biofidelic (Welbourne, 1998; Rudd, 1998). The amount of biomechanical data available when the original ALEX was designed was limited, and, by the time its design was published in the literature, research and development for the ALEX II had already begun (Hagedorn, 1995). Design specifications for the ALEX II were based primarily on volunteer and cadaver data found by Portier, *et al*. at Renault (1997) and Crandall *et al*. at the University of Virginia (1996). Under technical guidance by NHTSA, GESAC, Inc. and ASTC, Corp. each completed independent prototypes of the ALEX II in 1998. Both prototypes were tested for biofidelity, and Hagedorn, *et al*. (1998) presented the development of the NHTSA/ASTC version. Design features of both prototypes were combined and modified to create the Thor Lx (Figure 1), which is a joint design effort by GESAC and ASTC.

Figure 1: Thor Lx without tibia skin



Design specifications of the Thor Lx were based on volunteer and cadaver test results used in the ALEX II development. The Thor Lx incorporates many features which refine the biofidelity of the Hybrid III lower limb. These improvements include: 1) an Achilles tendon, 2) continuous joint stops, 3) anatomical centers of ankle rotation and 4) an axially compliant element in the tibia.

INSTRUMENTATION - The Thor Lx includes sensors that considerably improve the response measuring capabilities of the Hybrid III leg. Table 1 illustrates the instrumentation for the Thor Lx:

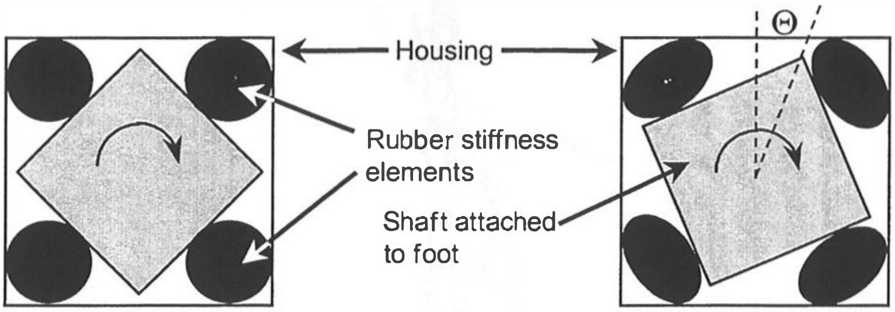
Table 1: Thor Lx Instrumentation

Location	Axis
Distal Tibia Load	X, Z
Distal Tibia Moment	X, Y
Proximal Tibia Load	X, Z
Proximal Tibia Moment	X, Y
Achilles Tendon Load	Z
Ankle Rotation Potentiometers	X, Y, Z
Foot Acceleration	X, Y, Z
Tibia Acceleration	X, Y, Z

FOOT - The Thor Lx foot is comprised of a carbon fiber plate, which extends from heel to toe, surrounded by a foam rubber skin. The attachment point for the Achilles tendon is located posterior to the ankle joint, coincident with the axis of rotation for inversion and eversion. This eliminates the influence of the Achilles tendon on the inversion/eversion stiffness.

ANKLE JOINT – Initial inversion/eversion (xversion) and dorsiflexion/ plantarflexion (flexion) rotational resistance comes from Rosta devices, which increase resistive torque as the joint rotates. Figure 2 shows a sketch of the continuous joint stop (CJS).

Figure 2: Rosta CJS



Flexion and xversion joints also use external soft joint stops to prevent metal-to-metal contact during extreme rotations. As the ankle rotates near its range of motion limits, rigid structures on the foot or tibia compress rubber wedges, which increase the resistive torque and eliminate joint-stop discontinuities. Dorsiflexion resistance is further increased by the Achilles tendon, which begins to produce a resistive torque at about 10° of plantarflexion. Internal and external rotation use a shaft-and-collar arrangement, with rubber contacts at the joint stop.

Rotations about all three axes are independent of each other, and xversion and flexion have separate, anatomically located centers of rotation. Flexion occurs primarily at the talar joint in the human, and xversion occurs at the subtalar joint. This is replicated in the Thor Lx by an xversion joint that is located 17 mm distal to the flexion joint.

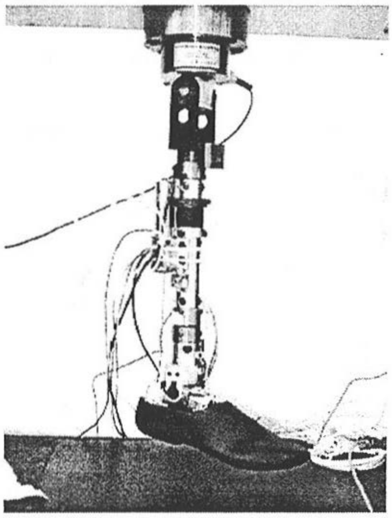
ACHILLES TENDON - Passive resistance from the human gastrocnemius and soleus calf muscles increases the rotational resistance to dorsiflexion. The Thor Lx mimicked this behavior with the inclusion of an Achilles tendon that attaches at the posterior end of the foot (calcaneus) and at the mid-shaft of the tibia. The tibia attachment point is in the Achilles tube, which includes a spring, load cell and foam compression elements.

TIBIA SHAFT - Unlike the Hybrid III tibia, the knee clevis center and the ankle joint of the Thor Lx lie on the long axis of the tibia shaft. This ensures that there are no artificial moments induced about the y-axis when there are z-axis loads present. The Thor Lx contains a tibia puck which introduces axial compliance to the long axis of the limb. The element adjusts the dynamic tibia force-time history to match human cadaver response over a range of input energies.

METHODOLOGY

QUASI-STATIC AXIAL LOAD - Quasi-static axial load tests were performed on a universal test machine. The proximal end of the tibia was mounted to the load cell on the cross-head of the test machine, and the foot was allowed to rest on the base as shown in Figure 3. Crandall, et al. (1996) performed similar tests with cadaveric specimens and other dummy limbs.

Figure 3: Thor Lx installed in universal test machine for axial testing



The tibia was loaded vertically with the foot in the neutral position. Zero displacement was defined when there was a 500 N preload measured in the cross-head load cell as suggested by Crandall, *et al*. (1996) to stabilize the ankle. The cross-head was lowered at a displacement rate of 22 mm/min until a predetermined load was reached. The maximum loads for the tests were set at 4 kN and 8 kN.

The response of the limb to quasi-static axial loading was based on force and displacement data measured directly from the universal test machine. The compression of the tibia compliance element was also measured and used in the data analysis.

QUASI-STATIC ANKLE JOINT MOMENT-ANGLE PROPERTIES - Ankle tests were performed on a six degree-of-freedom machine. This applied a known torque to the ankle joint with a constant displacement rate hydraulic piston. Figure 4 shows a schematic of this setup. Tests with other dummy limbs, cadavers and volunteers were conducted at the University of Virginia on the same test fixture (Crandall, 1996).

The tibia was securely bolted to the shin plate, and the plantar surface of the foot was bolted to the rotating fork. Only one degree-of-freedom was permitted for each Thor Lx test, and the center of rotation for the joint of interest was placed coincident with the axis of rotation of the test device. The force applied by the piston was related to the moment in the ankle joint by the radius at which the load was applied. A feedback control system was implemented to reverse the direction of rotation when a preset torque was reached at the ankle. Figure 5 shows the Thor Lx mounted in the test fixture for inversion/eversion tests.

Figure 4: Six DOF ankle rotation test fixture

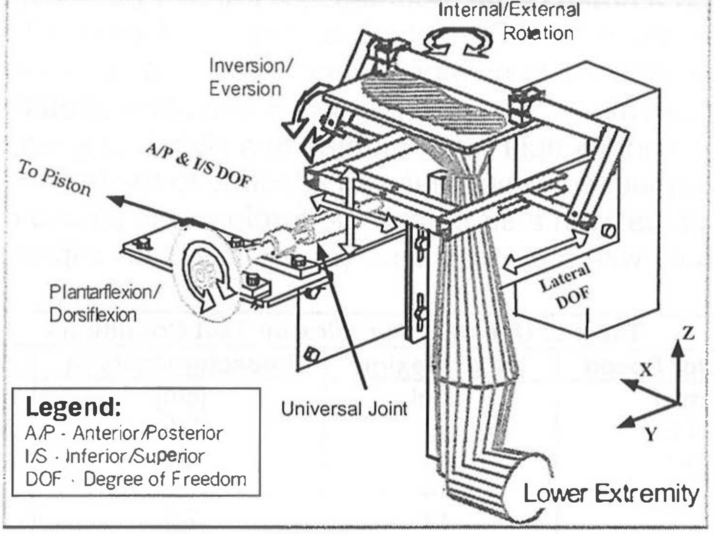
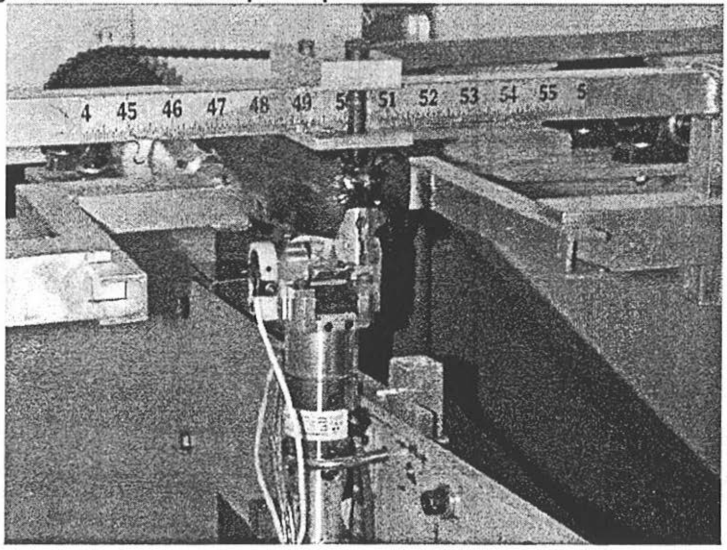


Figure 5: Thor Lx setup for quasi-static inversion/eversion test



MASS AND MOMENTS OF INERTIA - The Thor Lx was separated at the ankle joint and weighed. The leg segment included the portion of the ankle joint proximal to the flexion joint, Achilles hardware, knee clevis and tibia skin. Due to the complex ankle geometry with non-coincident axes of rotation, the intermediate segment (talus) between the flexion and xversion joints was included with the foot segment. Moments of inertia for the segments were determined using a three-wire torsional pendulum. The mass and moments of inertia were determined with the segment fully instrumented. The instrumentation cables were independently supported.

DYNAMIC DORSIFLEXION – A dynamic load was applied to the ball of the foot in order to determine the dynamic response of the ankle joint in dorsiflexion. This series of tests was performed with the Thor Lx and a Hybrid III with 45° dorsiflexion ankle and soft joint stop. Similar tests were performed by Portier, et al. (1997) at Renault using cadaver limbs and Hybrid III dummy limbs.

Dynamic dorsiflexion tests were conducted using a compound pendulum, which impacted a brake pedal mounted to a transfer piston at velocities between 2 m/s and 5 m/s. Pendulum velocities, ballast weights and impact cushions were changed to provide a variety of loading conditions. The impact cushion is a foam disc on the transfer piston that attenuates the load from the impactor. The Thor Lx tibia was mounted to a Hybrid III knee, which was mounted to a simulated femur that was attached to the test fixture. The tibia was held horizontal with a strap, and the forefoot was placed on the brake pedal and held in place with a piece of tape (which tore upon impact).

Table 2: Dynamic Dorsiflexion Test Conditions

Run	**Impactor Speed**	**Initial Flexion**	**Impactor Cushion**	**Effective Mass**
	[m/s]	[deg]	[cm]	[kg]
9.1	4.2	-14	2.5	18.0
9.2	5.3	-14	2.5	18.0
9.3	1.9	-14	2.5	20.8
9.4	4.1	-14	2.5	20.8
9.5	5.2	-14	2.5	20.8
9.6	4.2	-13	1.3	18.0

Foot positioning differed between the Hybrid III and Thor Lx because of the difference in the ankle joints. The lack of restoring torque in the Hybrid III ankle permitted vertical placement, while the Thor Lx Achilles tendon and CJS neutral position forced the foot to be in a few degrees of plantarflexion prior to impact. There was no initial inversion or eversion, and the internal/external rotation degree of freedom was locked in all tests with the Thor Lx. Figure 6 shows the forced dorsiflexion test setup with the tibia skin removed. Positioning was made simpler without the tibia flesh, and the effects of testing without the skin were negligible in the data.

Data were sampled at 10,000 Hz and filtered at CFC180. The ankle response was calculated based on loads and rotations measured directly from the Thor Lx and Hybrid III leg, the formula used in this calculation is:

$$M_{ankle} = My_{distaltibia} + z_a \cdot Fx_{distaltibia} + m_{distaltibia} \cdot (z_{cg} - z_a) \cdot ax_{tibia}$$

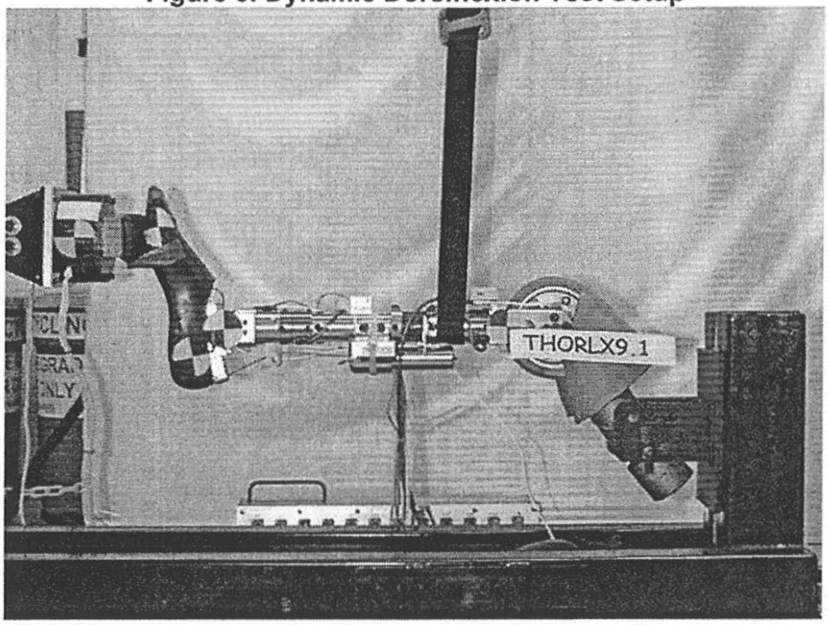
and

$$M_{ankle+achilles} = M_{ankle} + x_{achilles} \cdot F_{achilles}$$

Hybrid III instrumentation was supplemented with magnetohydrodynamic angular rate sensors to measure ankle rotations. Dorsiflexion moment versus angle characteristics were calculated using moments and forces measured in the tibia and Achilles tendon (for the Thor Lx). The $x_{achilles}$ used in the calculations was based on a static measurements of the moment arm of the Achilles about the flexion axis.

TOEPAN IMPACT - The limbs were installed in a test fixture which represented the lower limb of a vehicle occupant in a vehicle crash with toepan intrusion. The footplate, which simulated the vehicle's toepan, was installed at different angles relative to a transfer piston that was impacted by a pendulum

Figure 6: Dynamic Dorsiflexion Test Setup



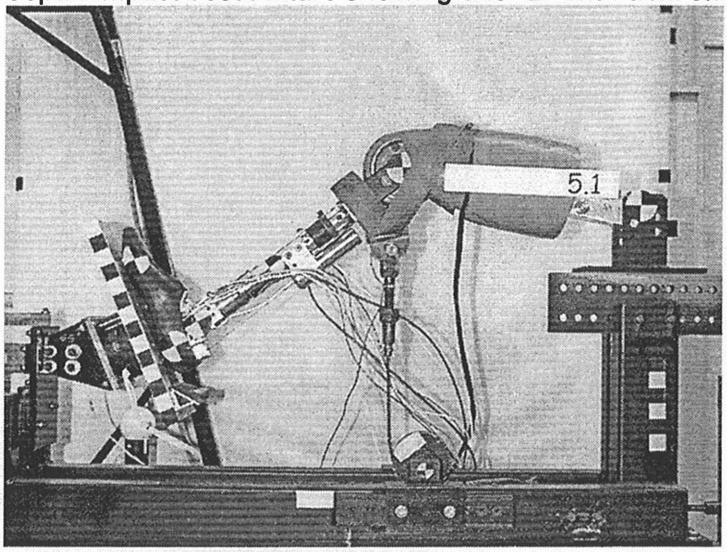
at speeds between 4 m/s and 6 m/s. Varying the speed, mass, and impactor foam cushion provided a range of impact severities. The toepan impact tests were also conducted at different initial foot and tibia conditions. A simulated muscle preload was applied to the leg for each test, and this was accomplished by placing a strap around the knee joint. The strap was connected to a spring with a cable, and the spring-cable arrangement was tightened prior to the test so that a one-half body weight (360 N) axial load was measured in the tibia. Table 3 shows the initial conditions for the pendulum impact tests. Figure 7 shows the toepan impact test setup.

Table 3: Toepan Impact Test Conditions

Run	Impactor Speed	Effective Mass	Impactor Foam	Initial Flexion
	[m/s]	[kg]	[cm]	[deg]
5.1	4.1	20.8	7.6	13
5.2	6.2	20.8	7.6	13
5.3	6.2	20.8	7.6	-13
5.4	6.1	20.8	7.6	-14
5.5	5.5	15.2	7.6	2 (10° eversion)
5.6	5.4	15.2	7.6	2 (10° inversion)
5.7	6.0	20.8	2.5	12
5.8	5.9	23.8	2.5	0

The axial load response of the limb was the primary concern in the toepan tests. Plantar surface loads (for Thor Lx), tibia loads and moments, and rotations between the foot and tibia were measured. Data were sampled at 10,000 Hz and filtered to CFC180. Crandall (1994) and Klopp (1995) present more information about the test procedure.

Figure 7: Toepan Impact Test Fixture showing Thor Lx with tibia skin removed



RESULTS

QUASI-STATIC AXIAL LOAD - Force versus displacement data were measured both with the test machine and the Thor Lx instrumentation. Table 4 lists the data obtained from the tests. Figure 8 shows the applied force and displacement measured from the universal test machine. Figure 9 shows the tibia force and compression of the tibia puck.

Table 4: Quasi-static axial load test results

Run	Max Applied Load [N]	Heel Compression [mm]	Max Puck Comp [mm]
1	7960	6	16
2	7590	6	15.5
3	4330	4	15.5
4	4590	3.5	15.5
5	7830	6	16
7	7820	6	15.5

Figure 8: Cross-head force/displacement

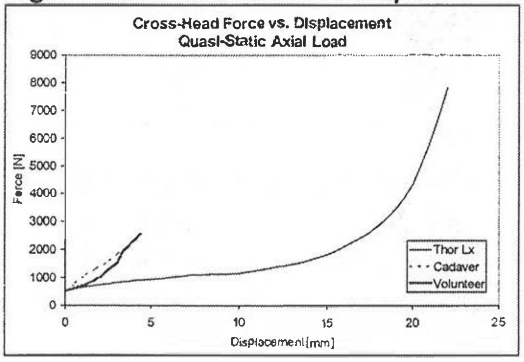
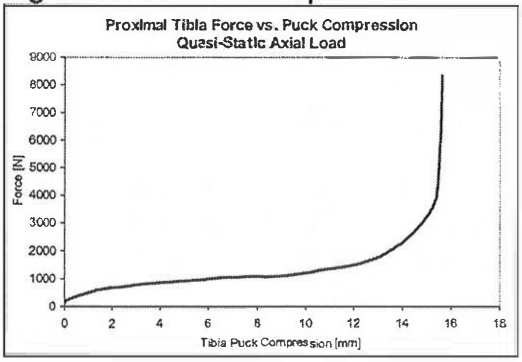


Figure 9: Puck force/displacement



QUASI-STATIC ANKLE JOINT MOMENT-ANGLE PROPERTIES – Ankle moment versus angle responses for the ankle in dorsiflexion, plantarflexion, inversion and eversion are plotted in Figures 10-13. The ankle moment in dorsiflexion includes effects from the Achilles tendon, which superimposes additional resistance to rotation that is a function of the Achilles tension and moment arm. Figure 14 shows the Achilles tendon force as a function of flexion angle.

Figure 10: Dorsiflexion response

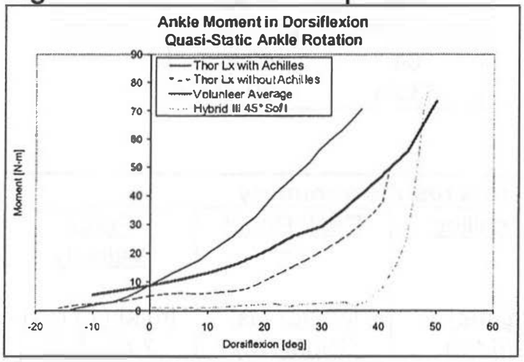


Figure 11: Plantarflexion response

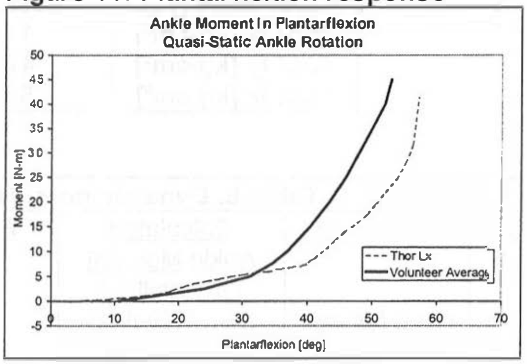


Figure 12: Inversion response

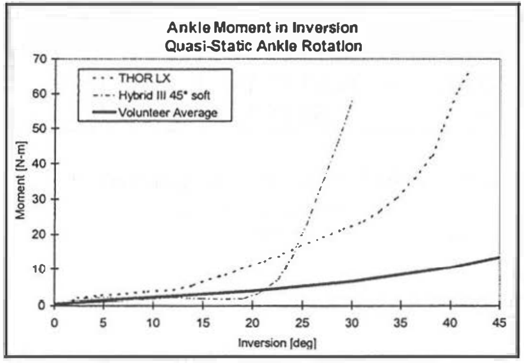


Figure 13: Eversion response

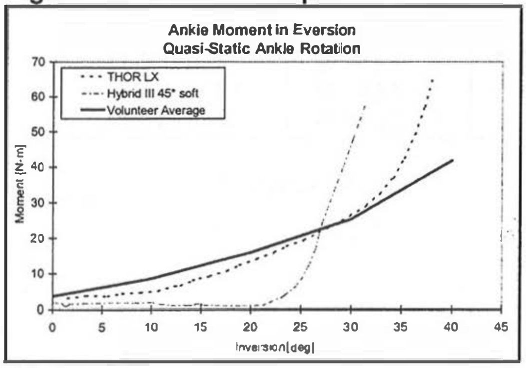
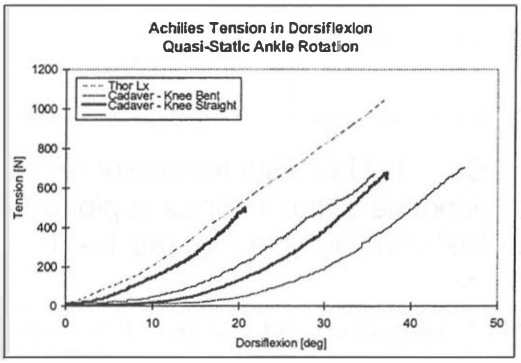


Figure 14: Achilles tension



MASS AND MOMENTS OF INERTIA – Mass and moment of inertia values are in Table 5, with cadaver and Hybrid III data from Crandall (1996).

DYNAMIC DORSIFLEXION – Table 6 shows a results summary from the dynamic dorsiflexion tests. A plot of the calculated ankle moment versus flexion (continuous joint stop plus Achilles moment) is shown in Figure 15, and the Achilles tension in Figure 16. Cadaver data is from Portier (1997).

Table 5: Mass and moment of inertia results			
	Cadaver Avg.	Hybrid III	Thor Lx
Leg Mass [kg]	3.19±0.33	3.64	3.89
Leg Ix [kg-cm²]	534.3	913.66	320
Leg Iy [kg-cm²]	534.3	913.55	300
Leg Iz [kg-cm²]	38.8	35.63	17.2
Foot Mass [kg]	0.99±0.11	1.48	1.30
Foot Ix [kg-cm²]	11.4	11.87	5.1
Foot Iy [kg-cm²]	47.4	64	42.8
Foot Iz [kg-cm²]	52.1	63.25	39.0

Table 6: Dynamic dorsiflexion test results summary					
Run	Peak Flexion	Calculated Ankle Moment (w/ Achilles)	Peak Achilles	Peak Pedal Fz	Pedal Velocity
	[deg] (@ ms)	[N-m] (@ flex)	[N] (@ ms)	[N] (@ ms)	[m/s] (@ ms)
9.1	30.7 (60.0)	74.2 (47.0)	1062 (53.9)	1985(7.2)	2.4 (11.4)
9.2	37.6 (46.9)	106.0 (44.8)	1509 (44.6)	6484 (5.3)	4.5 (9.7)
9.3	18.9 (75.5)	43.0 (66.6)	595 (66.7)	1068 (9.1)	2.1 (18.2)
9.4	35.4 (54.6)	89.6 (52.1)	1293 (52.6)	3671 (6.6)	3.8 (12.9)
9.5	38.3 (43.1)	120.5 (40.5)	1650 (40.9)	8321 (5.1)	4.8 (8.9)
9.6	34.8 (57.2)	81.8 (47.8)	1189 (51.3)	6652 (4.1)	3.7 (7.2)

Figure 15: Ankle moment

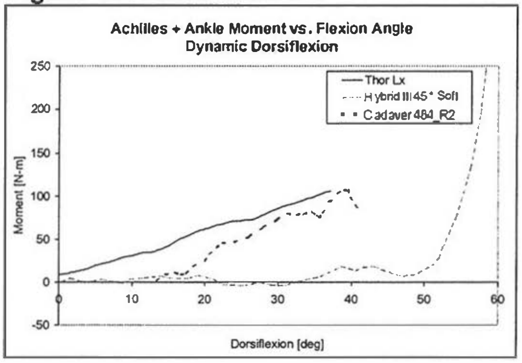
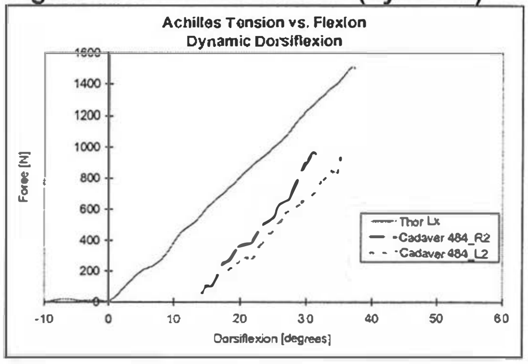


Figure 16: Achilles tension (dynamic)



TOEPAN IMPACT – Table 7 lists important results from the pendulum tests. The axial load response of the Thor Lx is plotted with the response of cadaver limbs for four test conditions in Figures 17-20. See Table 3 for details on the impact conditions.

Table 7: Toepan impact test results summary						
Run	Impactor Speed	Footplate Fz	Foot Z-Axis Accel	Tibia Z-Axis Accel	Max. Ankle Flexion	Peak Distal Tibia Fz
	[m/s]	[N] (@ms)	[g's] (@ms)	[g's] (@ms)	[deg] (@ms)	[N] (@ms)
5.1	4.1	2029 (18.0)	-18.4 (15.8)	-14.9 (9.5)	33.2 (74.8)	-2122 (21.3)
5.2	6.2	5359 (13.9)	62.2 (56.7)	-47.5 (14.6)	38.2 (56.6)	-4107 (15.0)
5.3	6.3	5624 (19.7)	-49.8 (14.6)	-58.2 (14.9)	8.3 (59.2)	-6017 (20.2)
5.4	6.0	6864 (18.8)	-78.2 (13.6)	-89.7 (13.8)	11.1 (64.1)	-9001 (18.7)
5.5	5.5	2691 (16.1)	-33.4 (14.6)	-28.4 (14.6)	16.9 (68.9)	-2736 (17.8)
5.6	5.4	2909 (14.8)	-40.0 (14.1)	-35.8 (13.9)	17.5 (63.1)	-2768 (17.3)
5.7	6.0	8791 (5.7)	-231.2 (6.3)	-237.9 (6.4)	37.9 (56.3)	-4436 (7.0)
5.8	5.9	8611 (6.1)	-222.0 (6.5)	-284.3 (6.4)	29.9 (80.1)	-5942 (10.8)

Figure 17: Axial load for Thor Lx 5.2

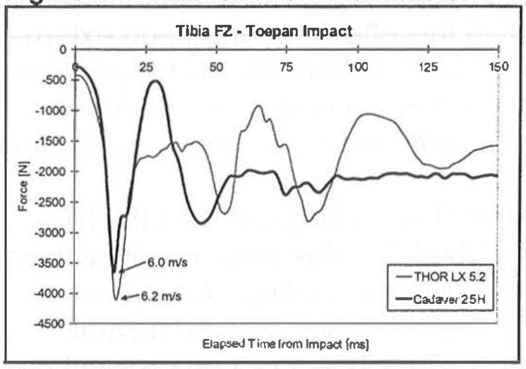


Figure 18: Axial load for Thor Lx 5.6

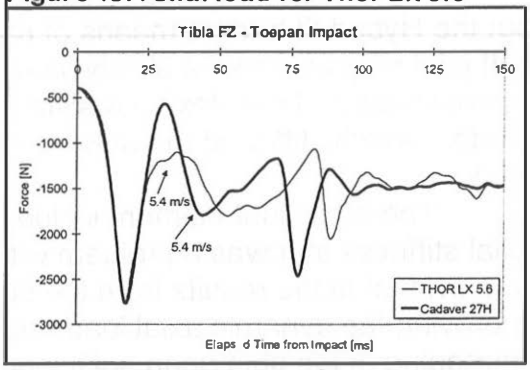


Figure 19: Axial load for Thor Lx 5.7

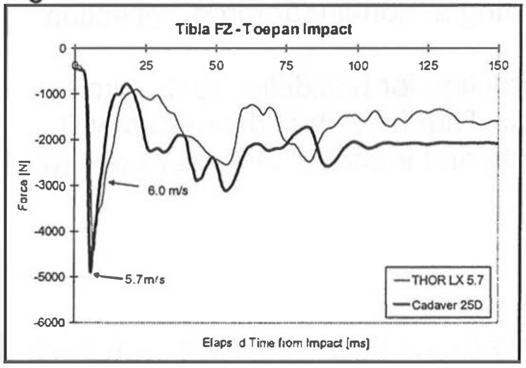
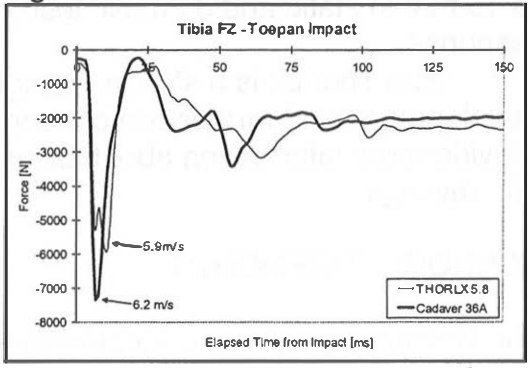


Figure 20: Axial load for Thor Lx 5.8



DISCUSSION AND CONCLUSIONS

The results from this testing indicate that the Thor Lx is an improvement over the Hybrid III dummy lower extremity. Design features that limited the biofidelity of the Hybrid III lower extremity have been fixed, and the Thor Lx provides a more realistic representation of the human lower limb suitable for crash testing.

Instrumentation alone made the Thor Lx an improved test device, since the Hybrid III only measured tibia loads. Plantar surface load cells, ankle potentiometers, foot and tibia accelerometers, and the Achilles tendon load cell help to characterized more completely the impact event. A possible design change would be the inclusion of a displacement transducer to measure the tibia compliant element compression.

Geometry and mass properties of the Thor Lx are improvements over the Hybrid III as well. The shape of the tibia shaft better resembles that in the human, and axial loads produce no artificial bending as in the Hybrid III. Replacement of the ball and socket ankle joint with non-coincident pin joints mimics the talar and sub-talar joints in the human. The Thor Lx tibia mass did not change much relative to the Hybrid III. The additional hardware on the Thor Lx offset mass lost using lighter materials. Inertial properties of the Thor Lx are lower due to the materials used and the locations of the additional hardware. The Thor Lx foot is lighter than the Hybrid III foot, even with the added instrumentation.

Continuous joint stops in the Thor Lx vastly improved the response of the ankle in static and dynamic settings. Effects of passive and active musculature in the human tend to increase the rotational resistance with increased rotation, but the Hybrid III had no means of replicating this effect. Internal and external soft joint stops created a slowly increasing resistance that eliminated joint stop discontinuities. Dorsiflexion resistance was further increased by the Achilles tendon, which stiffened the ankle joint significantly more than the CJS element alone.

The compliant element included in the Thor Lx tibia reduced the high axial stiffness that was a problem with the Hybrid III. This reduction in stiffness was evident in the results from the static and dynamic testing. As a result of improving the dynamic axial load response, the tibia puck allowed a small shortening of the tibia upon sufficient loading. The tibia puck compressed close to 16 mm in static and dynamic tests, creating a non-linear force-deflection response.

The Thor Lx is a step in the right direction for biofidelic crash dummy development, and further comparison of the Thor Lx with cadaver data will provide more information about its biofidelity and improvement over previous dummy legs.

ACKNOWLEDGEMENTS

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